

THE RELATION BETWEEN CARBON MONOXIDE EMISSION AND VISUAL EXTINCTION IN CLOUD L134

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ABSTRACT

Emission from the $J = 1 \rightarrow 0$ transition of carbon monoxide has been mapped over an area of $40' \times 55'$ in cloud L134, and visual extinctions over the entire cloud have been obtained by means of star counts. Line intensities of ≥ 2 K are observable down to an extinction level of about one magnitude. From observations of the $J = 1 \rightarrow 0$ transition of the ^{13}CO isotopic species at 18 locations in the cloud, we have found a linear correlation between the local thermodynamic equilibrium (LTE) column densities of ^{13}CO and magnitudes of visual extinction.

Subject headings: molecules: interstellar — nebulae: individual

I. INTRODUCTION

The value of carbon monoxide (CO) as a probe of interstellar dust clouds has been well established by numerous workers during the past five years (e.g., Penzias *et al.* 1972; Dickman 1975a; Tucker, Kutner, and Thaddeus 1973). With present receiver sensitivities, radio emission from its 2.6 mm, $J = 1 \rightarrow 0$, transition can be readily detected from almost any cloud where the visual extinction A_v exceeds 1 mag. At the gas number densities inferred for such clouds ($n \geq 100 \text{ cm}^{-3}$), most of the hydrogen gas is believed to be in the form of molecular hydrogen (Hollenbach and Salpeter 1971), which is spectroscopically undetectable by ground-based observers. However, because of the ease with which CO can be detected in these regions, its radiofrequency transitions provide a means of delineating and studying the molecular hydrogen component of the interstellar medium, thus complementing the 21 cm observations of the atomic hydrogen component.

If CO is to serve as a useful "tracer" for molecular hydrogen, it is necessary to establish that the number densities of the two molecules are correlated over some range of conditions. In this paper we present a detailed study of the spatial relationship between CO emission at 2.6 mm and dust in the dark cloud L134 (Lynds 1962), from which we are able to obtain an approximate value for the ratio of CO column density to magnitudes of visual extinction over a range of A_v from ~ 1 to 5 mag. Column densities of CO are determined from observations of the 2.6 mm lines of both the CO and the ^{13}CO isotopic species at 21 locations in the cloud.

Visual extinctions over the entire cloud were obtained from star counts of the red Palomar Sky Survey print, using the method described by Bok and Cordwell (1973) and summarized below. Our work here complements a similar study made by Encrenaz, Lucas, and Falgarone (1975) of the much more massive cloud near ρ Ophiuchi, and a comprehensive study of the relation between CO emission and visual extinction in 37 interstellar dark clouds made by Dickman (1975b, 1976).

II. CO OBSERVATIONS

The CO observations of cloud L134 were made at the Millimeter Wave Observatory,¹ Fort Davis, Texas. The 5 m antenna was equipped with an uncooled mixer receiver (SSB noise temperature 1500–2000 K) and a 40-channel spectrometer which provided frequency resolution of 250 kHz (0.65 km s^{-1} at 115.27 GHz). Absolute intensities were calibrated by the usual chopper wheel technique, and one position in the cloud was observed repeatedly as a check. Values of the rms noise in the calibrated spectra ranged from 0.25 to 0.5 K. The half-power beamwidth of the antenna at the CO frequency is $2.6'$.

The $J = 1 \rightarrow 0$ transition of the common isotopic species was mapped at approximately two-beamwidth intervals, the map covering the area from which peak

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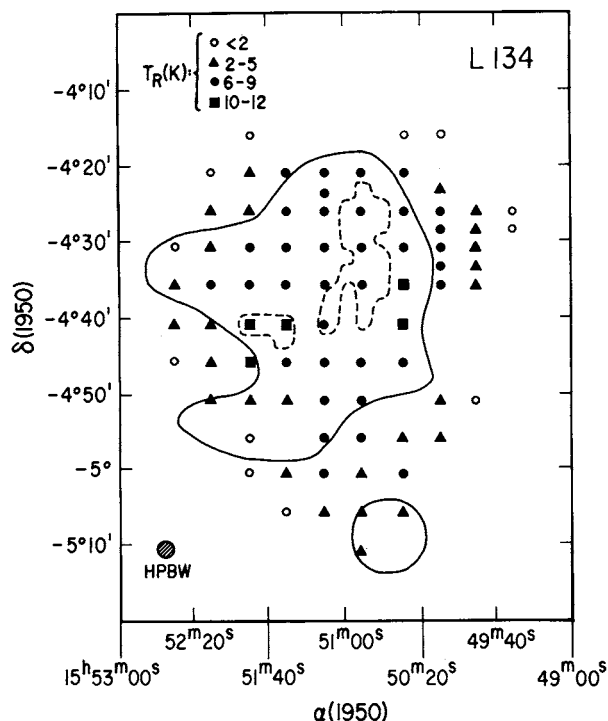


FIG. 1.—Peak intensities of CO lines at $v_{\text{LSR}} = 2.7 \text{ km s}^{-1}$ in L134. Solid line is the 1 mag extinction contour. Dotted lines enclose regions through which no stars are seen on the Palomar Sky Survey red print.

line intensities of $T_R \geq 2 \text{ K}$ could be observed. A summary of the observations is shown in Figure 1, where the CO emission is seen to extend over an area of $\sim 40' \times 55'$. The boundary of the observed emission is roughly coincident with the one-magnitude extinction contour determined from star counts; but in several locations the emission persists to even lower extinctions (see discussion in § V). The peak CO line intensity occurs at $v_{\text{LSR}} = 2.7 \text{ km s}^{-1}$ with a line width (full width at half-maximum) of $\sim 1.5 \text{ km s}^{-1}$. In the northeast quadrant there is a second velocity component at $v_{\text{LSR}} = 0.5 \text{ km s}^{-1}$ with a line width of $\sim 1.0 \text{ km s}^{-1}$.

The $J = 1 \rightarrow 0$ transition of ^{13}CO was observed at 21 locations where CO emission was present. Peak line intensities occurred at the same v_{LSR} as for the normal isotope, but the second velocity component was generally too weak to be observed in most positions. The width of the ^{13}CO line was somewhat smaller than that of the corresponding CO line, averaging about 1.1 km s^{-1} . A summary of the line intensities of CO and ^{13}CO at the positions where both were observed is given in Table 1.

III. STAR COUNTS AND VISUAL EXTINCTIONS

Visual extinctions in L134 were determined by the method of star counts described by Bok (1956) and by Bok and Cordwell (1973). Dickman (1975b, 1976) has discussed the application of this technique to small

TABLE 1
CO LINE INTENSITIES AND VISUAL EXTINCTIONS IN L134

Position * $\Delta\alpha, \Delta\delta$	$T_R(\text{CO})$ (K)	$T_R(^{13}\text{CO})$ (K)	A_v (mag)
0, $-30'$	6.9	2.0	0.5
0, $-20'$	9.5	3.8	1.8
0, $-10'$	8.9	6.8	≥ 7
0, $-5'$	7.0	5.6	≥ 7
0, 0.....	7.3	4.1	≥ 7
0, $5'$	6.7	3.6	1.2
$20^s, -30'$	7.3	1.4	0.7
$20^s, -25'$	7.1	2.7	1.2
$20^s, -20'$	9.5	1.5	0.8
$20^s, -15'$	9.0	3.7	4.8
$20^s, -10'$	2.9†	1.5	
	8.8	4.6	4.8
	4.6†	1.5	
$20^s, -5'$	6.7	2.8	2.7
$20^s, 0$	5.9	4.1	2.0
$20^s, 5'$	6.5	2.9	1.8
$40^s, -15'$	12.5	4.4‡	4.0
	4.7†		
$40^s, -10'$	7.3	3.8	2.3
	7.7†	1.6	
$40^s, -5'$	6.7‡	3.6‡	1.9
$40^s, 0$	6.1	2.6	1.0
	2.7†	< 1.5	
$40^s, 5'$	5.1	1.3	0.5
	1.5†	< 1.0	
$1^m, -10'$	6.0	2.9	2.0
	8.6†	2.3	
$1^m, 0$	3.7	1.0	0.5
	4.7†	< 1.0	

* Offsets are given with respect to $\alpha(1950) = 15^h50^m50^s$, $\delta(1950) = -4^\circ26'$.

† Second velocity at $v_{\text{LSR}} = 0.5 \text{ km s}^{-1}$ (see text).

‡ Blend of two velocity components.

areas of compact dust clouds, and has described in some detail the uncertainties associated with such an application. Accordingly, the procedure used to obtain visual extinctions from the star counts is reviewed here only briefly, with attention given to several points of difficulty that arose in connection with this particular source.

Because L134 lies rather far above the galactic plane ($b^{\text{II}} \sim 35^\circ$), where the stellar background is poor, extinctions were determined from the red (E) print of the Palomar Sky Survey in order to maximize the number of stars counted and thus achieve the best possible counting statistics. A transparent, rectilinear grid of squares (reseau) was placed over the image of the cloud and the number of stars, n_i , in each square was recorded. In addition, the number of stars in a nearby reference field, n_0 , was also obtained. The numbers n_i and n_0 were then scaled to equivalent star numbers for an area of one square degree, N_i and N_0 . Comparison of the differences ($\log N_0 - \log N_i$) with van Rhijn's (1929) tabulated values of $\log N_m$, where N_m is the number of stars per square degree brighter than magnitude m for the area of the sky in which L134 lies, then yielded $A_{R,i}$, the extinction in each reseau element at the print wavelength $\lambda \approx 6500 \text{ \AA}$.

Since van Rhijn's tables give the surface density of stars as a function of old photograph magnitude (essentially equivalent to modern blue magnitudes at $\lambda \approx 4300 \text{ \AA}$), the values of A_R^i obtained above will be correct only if the corresponding density function at red wavelengths obeys certain restrictions. These have been discussed elsewhere (Dickman 1975*b*, 1976); for present purposes it is sufficient to note that if star counts at both blue and red wavelengths are available for an object in which a standard reddening law is assumed, limits can be placed on the degree to which values of A_R^i derived from the van Rhijn density function are correct. Such a check was carried out for L134 by making star counts from the blue (O) Palomar print; and the results indicated that our direct use of the van Rhijn tables to obtain red extinctions resulted in less than a 15 percent error for each A_R^i .

The choice of an optimum reseau size for the star counts in L134 was complicated by the rather poor stellar background to this source. A reseau square small enough to adequately resolve the opaque core of the object would have yielded large uncertainties in the extinctions, because of the small number of stars per box. On the other hand, a larger reseau scale would have tended to blur the geometry of the opaque regions of this cloud, and, more important, would have produced grossly misleading underestimates of the extinction in those regions. To reconcile these two contrasting tendencies, the (red) star counts were performed twice, once using a moderate (5'5) reseau mesh, and once using a smaller (2'2) mesh. The 5'5 square size was sufficient to yield accurate measures of A_R over most of the cloud, where the extinction varies relatively slowly. The counts made with the finer grid were then used to obtain lower limits to the extinctions in the two areas of L134 where no stars could be seen (see Fig. 1), and to determine the extinction near the edges of these opaque regions. A lower limit to the extinction of an opaque region was obtained by assigning to it a count of one star.

It is assumed that the variation of extinction with wavelength in L134 follows the usual interstellar reddening law (e.g., Whitford 1958); visual extinctions were therefore obtained from their red wavelength counterparts via the relation $A_v^i = 1.2A_R^i$. For comparison with CO column densities, we averaged the resulting visual extinctions over the radio telescope beam. We estimate that the values of the visual extinctions used in this comparison possess an uncertainty of less than about 1 mag.

IV. PROPERTIES OF L134 FROM CO OBSERVATIONS AND STAR COUNTS

A lower limit to the mass of L134 can be obtained directly from the star counts if one adopts the standard value of the gas-to-extinction ratio, $N_H/A_v = 2.5 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1}$ (Jenkins and Savage 1974). Assuming a distance to L134 of 150 pc (Heiles 1968), we find $M_{L134} > 60 M_\odot$, the inequality arising from the fact that in the opaque core of the cloud where no

stars are visible only a lower limit to the visual extinction is obtained.

The mass of the opaque core alone (the larger opaque area in Fig. 1) is found to be $M_{\text{core}} > 25 M_\odot$; thus about half or more of the mass of the entire cloud is contained in a small central condensation. Although visual extinctions are, strictly speaking, a measure of the column density of the gas, the strong concentration of material in a small region must in fact reflect an increase in the number density of the gas; otherwise the cloud would have a highly improbable shape. Additional evidence for an increased density in the core region is provided by the recent detection there of HCN (Snyder and Hollis 1976).

Since a centrally peaked density distribution is a possible indicator of a cloud undergoing gravitational collapse, we examine here whether the remainder of our data are consistent with this hypothesis. First, an upper limit to the Jeans length, λ_J , can be estimated by assuming L134 to be spherical, homogeneous, and nonrotating, and by using the kinetic temperature derived from the maximum observed radiation temperature ($\sim 12 \text{ K}$) of the ^{12}CO 2.6 mm transition (since this line is undoubtedly thermalized and optically thick toward the cloud center). We obtain $\lambda_J < 1.3 \text{ pc}$, compared to an average cloud diameter of $\sim 2.6 \text{ pc}$, where the inequality follows from the lower limit to the cloud's mass. This simple analysis therefore indicates that L134 is roughly twice the size of the largest condensation of its mean density and temperature that could maintain itself in equilibrium against self-gravitation. The presence of the central condensation will further increase the tendency toward gravitational instability, because of the resulting enhancement of gravitational potential energy. We note also that a rotation sufficient to stabilize the cloud would produce a systematic shift in the CO v_{LSR} of at least 1.6 km s^{-1} across the face of L134, whereas the spectral resolution used in this work enables us to preclude any shift greater than 0.65 km s^{-1} .

If turbulence of the order of magnitude required to explain the observed spectral line widths is present in L134, it will contribute an effective pressure sufficient to prohibit collapse. However, the difficulty of accounting for an energy source to maintain supersonic turbulence and the incompatibility of the observed line profiles with a turbulent model make it uncertain that such motions can play a significant role in the dynamics of dark clouds (see discussion in Dickman 1975*b*). It is significant, therefore, that in the absence of turbulence the observed line widths that would result from gravitational collapse are of the right magnitude suggested by the cloud's radius and mass. Indeed, we find the free-fall velocity expected at the boundary of the CO emission to be $v_{\text{ff}} \geq 0.63 \text{ km s}^{-1}$. For a spherical cloud, this should result in a line width toward the cloud center of $\Delta v \approx 1.4v_{\text{ff}}$ (de Jong, Chu, and Dalgarno 1975), or, for L134, $\Delta v \geq 0.9 \text{ km s}^{-1}$. Given the uncertainties in the distance and geometry of L134, the agreement with observation is entirely satisfactory; and the hypothesis of gravitational collapse is therefore reasonably self-consistent.

V. COLUMN DENSITIES OF CARBON MONOXIDE

In the absence of detailed information about the density and thermal structure of L134, we have computed column densities of ^{13}CO by assuming uniform and equal excitation temperature of both CO and ^{13}CO along the line of sight (see Penzias *et al.* 1972; Dickman 1975a) at each location where the lines of both isotopic species were observed. These assumptions are equivalent to the approximation of LTE; the magnitudes of the errors associated with this procedure are discussed below.

The plot of ^{13}CO column density versus visual extinction is shown in Figure 2 and reveals a clear, roughly linear correlation between the two quantities. The average value of the ratio of $N_{^{13}\text{CO}}$ to A_v derived from the data points corresponding to $A_v < 5$ mag is

$$N_{^{13}\text{CO}}/A_v = 3.8 \pm 1.5 \times 10^{15} \text{ cm}^{-2} \text{ mag}^{-1},$$

where the quoted error is the formal standard deviation of the values of the ratio at 18 locations in the cloud. Using the standard value for the gas-to-extinction ratio, we obtain, for the ratio of the column densities of ^{13}CO and molecular hydrogen, the value

$$N_{^{13}\text{CO}}/N_{\text{H}_2} = 3.0 \pm 1.2 \times 10^{-6}.$$

Assuming a lower limit of 40 for the isotope ratio $^{12}\text{CO}/^{13}\text{CO}$ (Wannier 1975), we obtain a lower limit to the fraction of carbon in CO of 20 percent. The

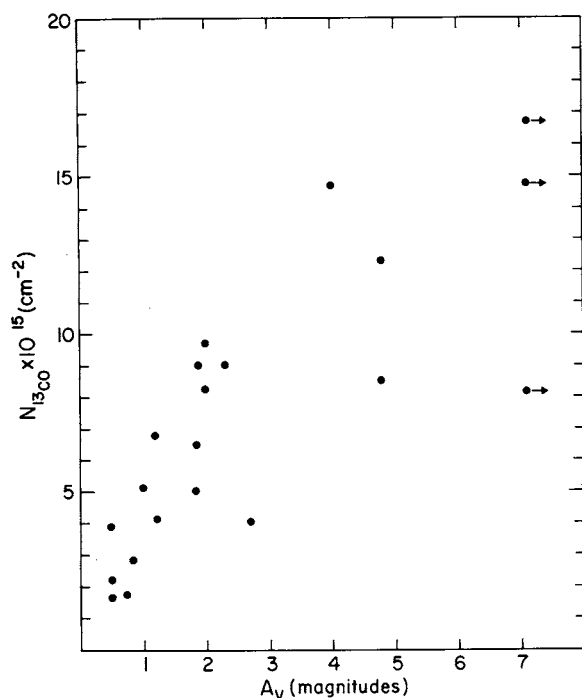


FIG. 2.—Column density of ^{13}CO versus visual extinction in L134.

existence of a linear relationship between carbon monoxide column density and visual extinction implies that this fraction is independent of A_v for $A_v < 5$ mag.

Two major sources of systematic error are associated with the above analysis. First, the LTE approximation probably overestimates the excitation temperature of the $J = 1 \rightarrow 0$ transition of ^{13}CO in regions of low extinction, where the gas number densities may be too small to thermalize the lower rotational levels. The size of the resulting error in the computed ^{13}CO column densities has been examined in detail for a variety of reasonable collapsing cloud models by Dickman (1975b), who finds that the error may become significant at extinctions less than about $1\frac{1}{2}$ mag, resulting in an underestimate of the ^{13}CO column density by up to a factor of 2 in the worst cases. A second systematic effect which can be important at low extinctions arises from the finite width of the telescope beam. Although we report positive detections of the ^{13}CO line at extinctions as low as $\frac{1}{2}$ mag, clumpiness or sharp density gradients in the area covered by the telescope beam can result in an underestimate of the lowest extinctions at which ^{13}CO emission can be observed. Since both these effects are worst near the cloud edges, our results for $A_v > 1$ mag should not be too strongly affected. Indeed, in comparing our results with those obtained for other dust clouds, we find that our correlation is in generally good agreement with those obtained by Dickman (1975b) and by Encrenaz, Lucas, and Falgarone (1975); some discrepancy with the latter work is evident only at extinctions less than about 2 mag.

VI. CONCLUSIONS

The validity of using CO as a tracer for molecular hydrogen and for using its millimeter-wave transitions to determine the abundance of H_2 in interstellar clouds (see, for example, Gordon and Burton 1976) is supported by the results of this work. In L134, a prototypical cool dust cloud, we find that CO emission at a wavelength of 2.6 mm is easily detected from areas of the cloud whose visual extinctions are as low as 1 mag; and thus the CO emission delineates more than 95 percent of the cloud's total mass. We find further that, for visual extinctions less than 5 mag, the LTE column density of ^{13}CO is a constant fraction of the molecular hydrogen column density. Thus, if a similar correlation between carbon monoxide and molecular hydrogen column densities is assumed to hold for more distant clouds for which visual extinctions are unobtainable, measurements of the ^{13}CO column densities in these clouds can be directly converted to hydrogen abundances without any additional assumptions about the line-of-sight geometry or isotopic ratios.

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REFERENCES

- Bok, B. J. 1956, *A.J.*, **61**, 309.
 Bok, B. J., and Cordwell, C. S. 1973, in *Molecules in the Galactic Environment*, ed. M. A. Gordon and L. E. Snyder (New York: Wiley), p. 53.
 de Jong, T., Chu, S., and Dalgarno, A. 1975, *Ap. J.*, **199**, 69.
 Dickman, R. L. 1975a, *Ap. J.*, **202**, 51.
 ———. 1975b, unpublished Ph.D. dissertation, Columbia University.

- Dickman, R. L. 1976, in preparation.
Encrenaz, P. J., Lucas, R., and Falgarone, E. 1975, *Astr. and Ap.*, **44**, 73.
Gordon, M. A., and Burton, W. B. 1976, *Ap. J.*, **208**, 346.
Heiles, C. E. 1968, *Ap. J.*, **151**, 919.
Hollenbach, D. J., and Salpeter, E. E. 1971, *Ap. J.*, **163**, 155.
Jenkins, E. B., and Savage, B. D. 1974, *Ap. J.*, **187**, 243.
Lynds, B. T. 1962, *Ap. J. Suppl.*, **7**, 1.
Penzias, A. A., Solomon, P. M., Jefferts, K. B., and Wilson, R. W. 1972, *Ap. J. (Letters)*, **174**, L43.
Snyder, L. E., and Hollis, J. M. 1976, *Ap. J. (Letters)*, **204**, L139.
Tucker, K. D., Kutner, M. L., and Thaddeus, P. 1973, *Ap. J. (Letters)*, **186**, L13.
van Rhijn, P. J. 1929, *Groningen Pub.*, Vol. **43**.
Wannier, P. G. 1975, unpublished Ph.D. dissertation, Princeton University.
Whitford, A. E. 1958, *A.J.*, **63**, 201.

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